PRECISION MEASUREMENT OF THE HIGGS BOSON MASS AND SEARCH FOR DI-LEPTON MASS RESONANCES IN $H \rightarrow 4\ell$ DECAYS USING THE CMS DETECTOR AT THE LHC

By

DANIEL “JAKE” ROSENZWEIG

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTORATE OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2022

I dedicate this to Jacob Myhre.

ACKNOWLEDGEMENTS

Without so many two-legged blessings along the way, I could never have made it to this point in my academic career. Thus, I give my unlimited thanks to the following people.

To my wife, Suzanne Rosenzweig, for showing me that dreams do come true. To my mother and father, Vicki and John, who always reassured me that I could achieve anything I put my mind to. Sleep peacefully, Mom. To my siblings, Alex, Ryan, Devin, Jace, and Claudia who reminded me that there was life outside of grad school.

To my mentor, Sheldon Friedman, and his wife, Rita Friedman (Rosenzweig), who chose to invest in my success at a young age To Sheldon's best friend, Dr. Bernard Khoury,

To my physics mentors, Professors Andrey Korytov and Guenkah Mitselmakher, for granting me the one-of-a-kind opportunity to work on the CMS Experiment at CERN. To Dr. Filippo Errico for his To Dr. Noah Steinberg To Darin Acosta, for spending hours of discussion on every t To the gentle gents who introduced me to the world of CMS, Brendan Regnery and Bhargav Joshi.

To my grad school comrades for showing me what it takes to survive the core courses, Dr. Atul Divakarla, Dr. Brendan O'Brien, Dr. Daniel Guerrero, and Dr. Vladimir Martinez.

To the grad students who tagged along in our "CMS Office Hours": Evan Koenig, Nik Menendez, Neha Rawal, John Rötter. And to the many students who let us practice our spiels: Sean Kent, Jeremiah Anglin, Cris Caballeros, Ari Gonzalez,

To my mentee, Matthew Dittrich, for

To my Polish roommates in Saint-Genis-Pouilly for showing me what home away from home feels like.

To the many moms who have offered unconditional support during our darkest times: Silet Wiley, Margaret Sherrill, Dawn Hood, Cyndi Reilly-Rogers.

To my childhood best friends (in order of appearance): Jish, Willis, Shane, Zac, Duck, Marcus for their constant clever competition which has shaped me into the determined man I am today.

And finally to Existence itself for this unpredictable, unbelievable blip of an experience called life.

TABLE OF CONTENTS

page

ACKNOWLEDGEMENTS 4

LIST OF TABLES 6

LIST OF FIGURES 7

CHAPTER

1 INTRODUCTION 9

2 THE CMS DETECTOR 10

2.1 Background Estimation 11

2.1.1 Irreducible Background 14

2.1.2 Reducible Background 14

3 SUMMARY 16

LIST OF TABLES

Tables page

LIST OF FIGURES

Figures page

2-1 Life-size poster of the CMS detector, taken during CERN Open Days 2019 in the SX5 warehouse where parts of CMS were assembled. 10

2-2 Points 1 through 8 along the LHC. Collisions occur at Points 1 (ATLAS), 2 (ALICE), 5 (CMS), and 8 (LHCb), whereas the remaining points are used for LHC beam maintenance and testing. 11

2-3 Cut out of the CMS detector showing its various subdetector components. 12

2-4 A transverse view of CMS showing the “filtration process” as different particles pass through different subdetectors. A positron (solid red line) curves due to the presence of the magnetic field and gets stopped in the ECAL, creating an EM shower. A photon (blue dashed line) does not get detected at all by the Silicon Tracker, since it has no electric charge. It continues through to the ECAL and makes a shower here, like the positron. Charged hadrons (solid green line) will show curved tracks from the Silicon Tracker, may leave some trace in the ECAL, but primarily get stopped by the HCAL creating hadronic showers. Neutral hadrons (dashed green line) do not interact with the tracker, and only undergo EM showers a little in the ECAL, but show most energy deposits in the HCAL. Muons (solid blue line) are detected by the Silicon Tracker and then mostly pass through the other subdetectors without interacting until they finally reach the Muon System. Using the Lorentz force law and knowing which direction the magnetic field is pointing, one can deduce the sign of the charge of the particle. Based on the radius of curvature from the trajectory, one can then calculate the momentum and energy of the particle. 13

CHAPTER 1
INTRODUCTION

The universe, while overwhelmingly vast, is comprised of a curiously small number of elementary particles. These particles and their strong, weak, and electromagnetic interactions with each other are accurately described by the Standard Model (SM). A major shortcoming of the SM was its inability to predict the masses of these particles.

This dissertation presents a precision measurement of the Higgs boson mass and using LHC proton-proton collision data from Run 2 data set from

The SM was not able to predict the masses of these particles until 1964 when the Brout-Englert-Higgs mechanism suggested that It wasn't until 1964 that the Brout-Englert-Higgs mechanism gave a self-consistent way to : by breaking the electroweak gauge symmetry of the vacuum would give rise to non-zero masses of the weak gauge be101osons. This would yield a secondary effect too: there should exist a fundamental scalar boson which is the quantum of the so-called "Higgs field". On July 4th, 2012, this Higgs boson was discovered.

At first glance, the universe appears to be an overwhelmingly vast and complicated place. However upon closer inspection, it is comprised of only a few different kinds of fundamental particles. Particle physics has given rise to the Standard Model (SM) which mathematically describes these constituents and their interactions with each other.

The Standard Model (SM) is an impressively accurate mathematical theory which describes the fundamental particles of the universe and the rules for their possible interactions. Problematically though, the SM predicts that all particles are massless.

Get to the Higgs boson.

Why is it important? Knowing the mass of the Higgs boson

CHAPTER 2
THE CMS DETECTOR

Figure 2-1. Life-size poster of the CMS detector, taken during CERN Open Days 2019 in the SX5 warehouse where parts of CMS were assembled.

Weighing in at 14,000 tonnes, standing 5 stories tall (15 meters), and reaching 29 meters long, the Compact Muon Solenoid (CMS) experiment is one of two general-purpose particle detectors at the LHC (Fig. 2-1). CMS is situated approximately 100 m under the earth at the fifth collision point (Point 5) along the LHC (Fig. 2-2). In 2012, both CMS and its competing experiment, ATLAS, independently discovered the Higgs boson.

As discussed in Section (TODO: REF), the LHC collides bunches of protons every 25 ns to produce thousands of new particles which then travel away from the IP. CMS is built around the IP in a series of concentric cylindrical subdetectors and two endcaps for nearly hermetic coverage so that most particles travel into and through CMS. The detector sports a 3.8 T solenoid, after which CMS was named, that creates a longitudinal magnetic field in the center of CMS. The magnetic field forces charged particles to follow momentum-dependent curved trajectories, thereby separating the particles for easier detection. Neutral particles remain unaffected.

Particles interact with the subdetectors, leaving “hits”. Hits are reconstructed into tracks. From the track curvature, deduce charge and momentum. Depending on which subdetector (or combination of subdetectors) was hit by the outgoing particles, the type of particle can be deduced. These subdetectors measure the properties of and carefully filter the outgoing particles in a clever way (Fig. 2-3).

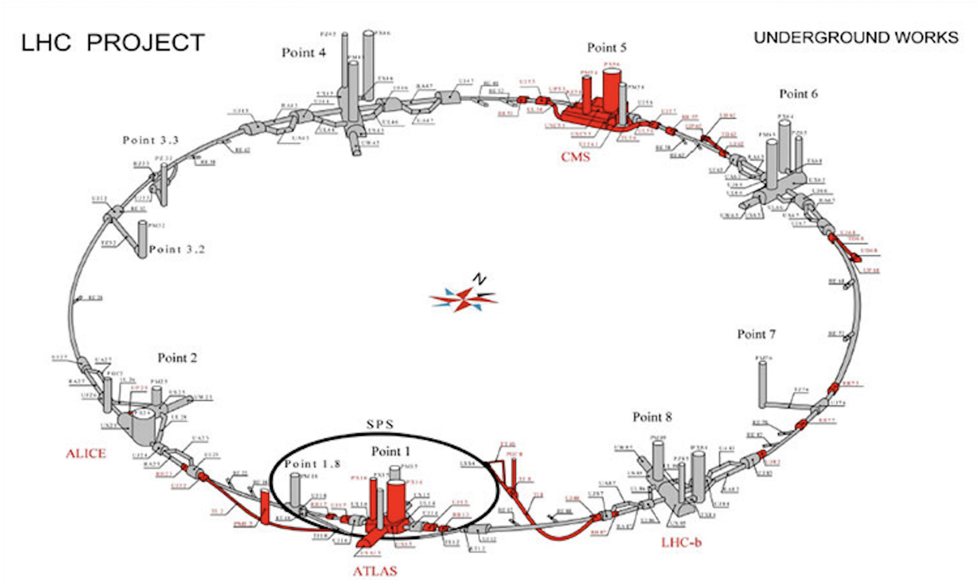

Figure 2-2. Points 1 through 8 along the LHC. Collisions occur at Points 1 (ATLAS), 2 (ALICE), 5 (CMS), and 8 (LHCb), whereas the remaining points are used for LHC beam maintenance and testing.

A few example particles and their associated tracks are shown in Fig. 2-4.

In the following sections, the various subdetectors are described in detail.

2.1 Background Estimation

Processes which pass the signal event selection (REF EVENT SELECTION) but are not actually the signal process of interest (HZZ4L) are called background processes. These background events spoil the purity of the signal events and introduce further uncertainty into the final Higgs boson mass measurement. Therefore, it is a priority to properly model and reduce the number of background events.

The two types of background processes present in the HZZ4L analysis are:

- irreducible background
- reducible background

and will be explained in full detail in the subsequent sections.

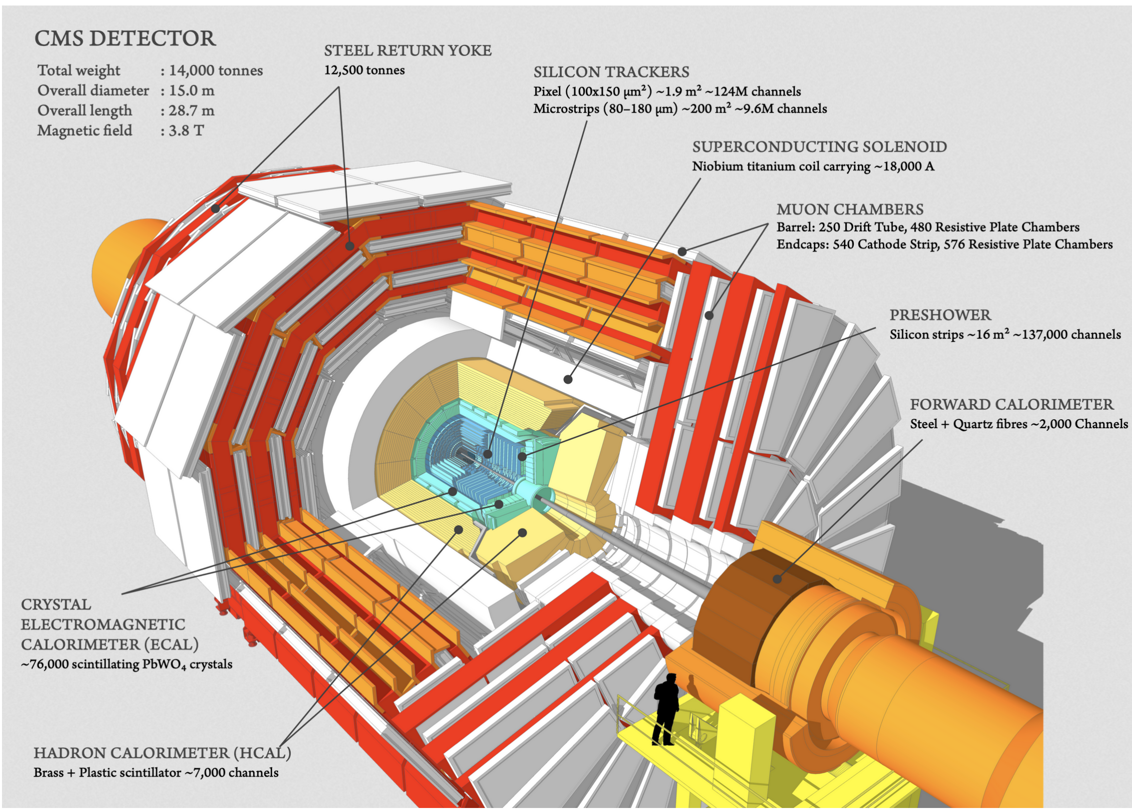

Figure 2-3. Cut out of the CMS detector showing its various subdetector components.

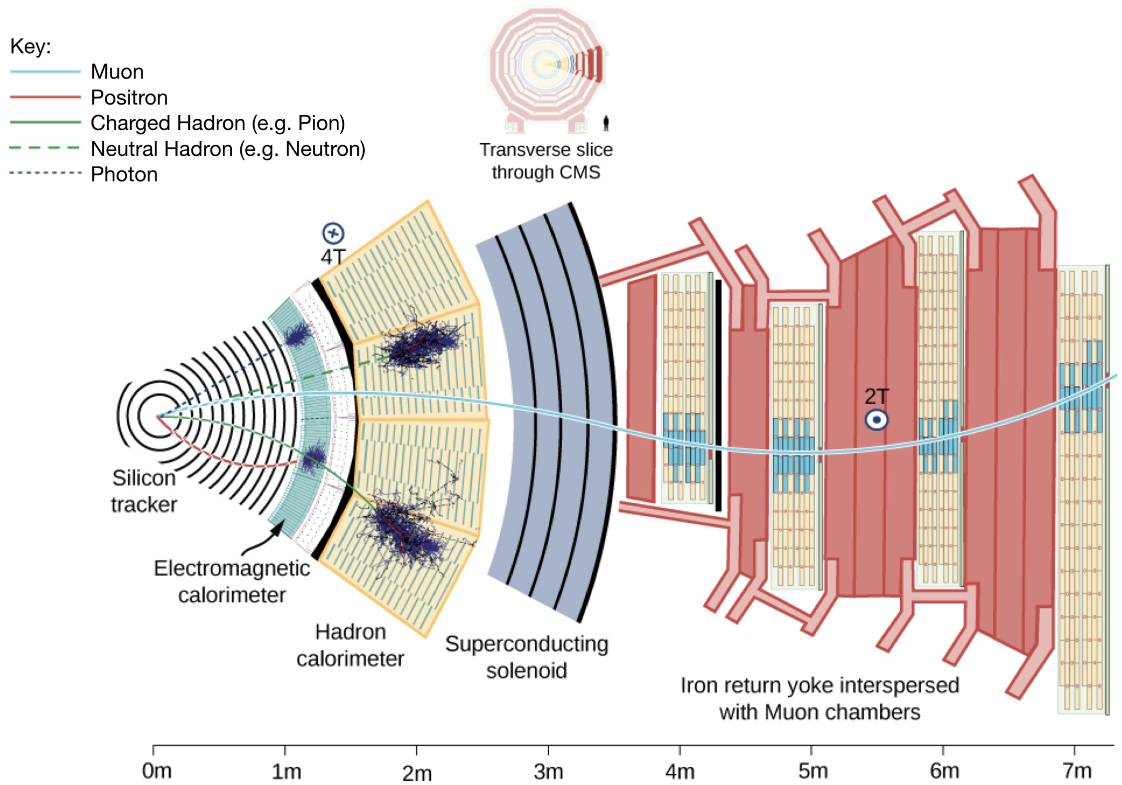

Figure 2-4. A transverse view of CMS showing the "filtration process" as different particles pass through different subdetectors. A positron (solid red line) curves due to the presence of the magnetic field and gets stopped in the ECAL, creating an EM shower. A photon (blue dashed line) does not get detected at all by the Silicon Tracker, since it has no electric charge. It continues through to the ECAL and makes a shower here, like the positron. Charged hadrons (solid green line) will show curved tracks from the Silicon Tracker, may leave some trace in the ECAL, but primarily get stopped by the HCAL creating hadronic showers. Neutral hadrons (dashed green line) do not interact with the tracker, and only undergo EM showers a little in the ECAL, but show most energy deposits in the HCAL. Muons (solid blue line) are detected by the Silicon Tracker and then mostly pass through the other subdetectors without interacting until they finally reach the Muon System. Using the Lorentz force law and knowing which direction the magnetic field is pointing, one can deduce the sign of the charge of the particle. Based on the radius of curvature from the trajectory, one can then calculate the momentum and energy of the particle.

2.1.1 Irreducible Background

The first kind of background process is that which produces two Z bosons which then decay into four prompt leptons. These four leptons typically get reconstructed as leptons which pass tight selection. Therefore, the event is tagged (incorrectly) as a 4-lepton signal event. Since these processes cannot be distinguished from the signal process and cannot be reduced, they are called irreducible backgrounds. The two irreducible backgrounds for the HZZ4L analysis are:

1. ggTOZZ (gluon-gluon fusion)

2. qqbarTOZZ (quark-antiquark annihilation)

2.1.2 Reducible Background

Besides irreducible backgrounds, there are other background processes that produce non-prompt leptons which are erroneously reconstructed as passing tight selection, due to detector imperfections. These leptons should have been rejected since they come from a non-signal process, the imperfect lepton reconstruction, these leptons appear to be signal leptons. Using careful event selection methods and more efficient detectors, these background processes can be reduced, hence the term reducible backgrounds. Reducible backgrounds include:

1. Z+jets

2. ttbar

3. WZ

4. qqbarTOZZ, ggTOZZ

Since reducible backgrounds are not eliminated entirely within the signal region, they must be modelled and estimated.

More concretely, reducible backgrounds have three main sources:

1. misidentifying light-flavor hadrons (e.g., PIONS) as leptons,

2. heavy-flavor hadrons which decay mid-flight into leptons,

3. and asymmetric photon conversions into electrons.

words.